A Method of Flow Stabilisation with High Pressure Reco ery in Short, Conical Diffusers

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1. Introduction

The problem of obtaining proper flow spreading together with useful pressure recovery across rapidly expanding diffusers is of considerable practical importance, Many different approaches to this end have, been reported in literature, e.g. vortex generators, screens or bailies, surface roughness, corrugations, etc., apart from the use of direct boundary-layer control. These methods have the common aim of preventing separation from the walls of the diffuser. With increasing expansion angle and area-ratio, however, the effectiveness of these methods either breaks down or is obtained at a high cost of pressure recovery.

This note describes a new method applicable to conical diffusers, originally developed for a particular configuration of 38° total angle and area-ratio 15. Steady exit flow with good uniformity of the velocity profiles was obtained by the use of radial splitters, with a pressure recovery coefficient (C_p) exceeding 0·6. Even higher pressure recovery performance was achieved with a dill'iiser of the same area ratio but having a reduced expansion angle *(20)* of 25°, while the flow spreading action of the radial splitters was found to persist at least up to an expansion angle of 50".

The present method is regarded as novel in that it docs not seek to eliminate separation in the dill'iiser. Rather, it relies upon a steady separated flow to achieve the flow spreading action, The radial splitters divide the conical diffuser into a number of identical triangular expanding passages, each of which contains a separation bubble of large relative size. Some qualitative experiments have been carried out to explore (he nature of this separated flow, and data is presented to guide the optimisation of the splitters for maximum pressure recovery in diffusers of different angles.

Notation

- A_s diffuser cross-sectional area in plane of splitter leading-edge,
- A_p blockage area at splitter apex for trip area).
- l splitter cut-off length (*see* HI*. I),
- L diffuser axial length.
- θ diffuser semi-cone angle,
- C_p pressure recovery coefficient $=(p_0-p_i)/q_i$, where
- p_0 exit static pressure,
- p_i inlet static pressure, and
- q_i inlet dynamic pressure.

2. Radial Splitters as Flow Spreaders

The use of splitters has been frequently attempted in a variety of three-dimensional diffuser configurations, usually in cruciform or egg-box arrangement, However, these have been largely *ad hoc* experiments and the results in many cases have proved inconclusive, The usual approach has been to split the given dill'iiser into a parallel s tem of smaller diffusers each having a reduced effective e ansion angle, which the flow would presumably negotiate vithout separation. In practice, difficulties have arisen due t

(*a*) unequal capture of mass flow in the diffe nt cells because of a non-uniform inlet profile, an

(*b*) excessive friction loss due to greatly i reased welled surface.

The extension of this principle to conical diffuse would require the use of conical sleeves in a concentric sembly to give a system of annular diffusers. This arran nent is also subject to the above-mentioned drawbacks and in addition poses practical difficulties relating to th manufacture, accurate alignment and support of the sle es.

It was reasoned that radial splitters would t only overcome the practical problems but also be more tolerant of the entry flow nonuniformity; as long as e inlet velocity profile was axi-symmetric, equal (low c turein the passages between Ihe radial splitters would be ssured.

Furthermore, the known characteristics of via us flow through triangular duets suggested that a rapid bt d-up of secondary flows along the inner corner of th splitter passages (which has the narrowest included angl would impart a natural tendency for flow spreading to rds the difl'uscr wall. This mechanism of flow disp cement associated with Ihe growth of Ihe corner bounc ry-layer appeared to he more elegant a solution than tl use of solid surfaces to force Ihe spreading of the f w, The possibility of complete separation in the inner co era was recognised, particularly for large dill'iiser angles. owever, it was expected that in such an event the emer ng flow would still be essentially axi-symmetric with double peaked velocity profile, which being unstab would rapidly mix, into a more or less uniform flow a ort distance from Ihe dill'iiser exit,

The radial splitter system adopted in this wo was an assembly of eight thin, flat vanes spaced at eq al angle (45°), and running nominally Ihe full length of t diffuser (Fig. 1). The choice of the number of vanes was e sentially a compromise between the desirability of a nar w inner corner (for promoting secondary flows) and the need to minimise wetted surface area. Limited tests wit six-vane radial splitters were also carried out.

3. Summary of Preliminary Investigation

The initial experiments that led to Ihe confir ation of the radial splitter concept have been reported i Ref, 1. The main results of the preliminary work (for a 8° total angle conical dill'iiser of area ratio 15) summari d below serve as a background to the more detailed inve igations which will be discussed in the later sections,

(*i*) With splitters having sharp (or well st amlined) leading-edges, there was no flow spread g, complete separation from the diffuser wall ccurred

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the flow consequently emerging as a steady, axi-symmetric jet (Fig. 2*a*).

(*ii*) An entirely different flow pattern was found with splitters having blunt leading-edges (Fig. 2*b*). Separation now occurred in the inner corners at the apex of the splitters and extended over most of the splitter length. The flow was fully attached to the diffuser wall. An identical flow pattern, dominated by a separation bubble in the inner corner was present in all the passages. The emerging flow was steady and practically uniform a short distance (i.e. 0·25 exit diameter) downstream of the exit plane. The pressure recovery, however, was very poor.

(*Hi*) The corner-bubble flow, leading to successful flow spreading action, was also produced with sharp leading-edge splitters by placing a separation trip (namely a small bead) symmetrically over the apex. The trip evidently duplicated the function performed by the blunt apex in (*ii*). A minimum trip size was needed for this purpose, below which the flow reverted to the centre-jet type described in (*i*). Using a minimum trip, a significant pressure recovery across the diffuser was achieved,

(*iv*) Further gains in pressure recovery were obtained by cutting away a short initial length (*l*) of the splitters (as indicated in Fig. 1), The minimum trip si/.e needed to establish the bubble-vortex flow was somewhat bigger with the cut-away splitters.

These early results appeared sufficiently promising to warrant a more detailed investigation for exploring the pressure recovery potential of the splitters in conical diffusers of other angles, and also to elucidate (he details of the flow mechanism. This was carried out with larger-scale diffuser models, as described in the following section.

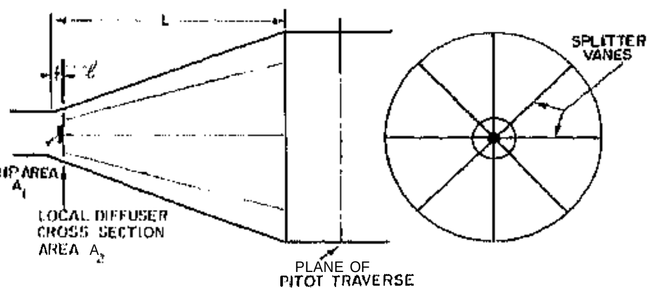

Figure 1. Radial splitter arrangement in conical diffuser.

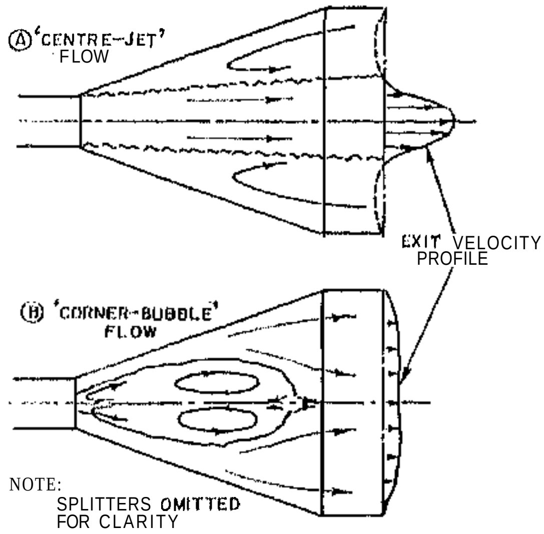

Figure 2. Types of flow in conical diffuser with radial splitter.

4, Tests with Conical Diffusers

Three diffuser models were tested, of total conical angle 25°, 38° and 50", all having an area-ratio of 15 (the second diffuser was thus geometrically similar to the model used in the preliminary investigations, section 3). The inlet diameter in each case was 3 in (0·08 m) with a 3 in (0·08 m) inlet length of constant diameter incorporated. All models were constructed of fibre-glass reinforced plastic with smooth internal surfaces.

The splitters were assembled from ⅛ in (3·2 mm) thick aluminium or plywood vanes with smoothened surfaces, bonded together accurately in a special jig. The leading-rages of the vanes were rounded off to an approximately elliptical shape, which was carried into the root (i.e. junction of the vanes) as far as possible. The separation trips were in the form of sharp-edged circular discs cut from thin plastic sheet, affixed concentrically on the splitter apex. The majority pf the tests were carried out with eight-vane splitters; limited tests were also done with six-vane splitters in the 25° and 38° diffusers.

The airflow was supplied by means of a commercial centrifugal blower via a stilling chamber and an axi-symmetric contraction, at a velocity of about 350 ft/sec (106·68 m/s) at Ihe diffuser inlet: (Reynolds number= 3.5 × 10⁵ . ed on the inlet diameter and air temperature of 40°C). The inlet turbulence level was about 0·5%. The diffusers discharged to atmosphere through a short tailpipe (approximately half exit diameter in length), which also a total-pressure rake with the plane of measurement 3 in m) (i.e. approximately quarter exit diameter dow of the exit plane of the diffuser, Fig. 1). This dista..ce was maintained to avoid misleading results due to the large flow inclinations that would inevitably occur (nearer the diffuser walls) in the exit plane when the flow was fully spread. By rotating the tailpipe with respect to the diffuser, the rake was positioned in the centre-plane of the different splitter passages in turn.

Accurate measurement of the exit velocity profile was rendered difficult because of the low velocities (about 20 ft/see (6·1 m/s) when the exit was running full) and the high turbulence level. The uniformity of the exit flow was, therefore, checked visually on a multi-tube alcohol manometer connected to the total pressure rake. An additional check on the exit-flow behaviour was made in each case using a tuft probe.

Mow visualisation in the splitter passages was achieved by injecting a mixture of paraffin and titanium dioxide in the inner corners through a long hypodermic tube. When the corner bubble flow was present, the oil was carried along the corner by the reverse flow up to the apex and then swept downstream essentially along the bubble boundaries on the vane surfaces. This procedure allowed a rapid visualisation of the most interesting features of the flow (Fig, 3).

6. Results and Discussion

Jn the 25° and 38° diffusers, the eight-vane splitters were found to be effective without using a separation trip, for all values of cut-off length (*l*) from zero to the optimum (i.e. for maximum C_p). Tho drop in C_p caused by a small increment in l beyond the optimum was restored by applying a critical sized trip (Fig. 4).

In the 50° diffuser, however, the splitters were effective only with the application of a trip even for $l=0$. A critical trip size was determined to give maximum C_p for each value

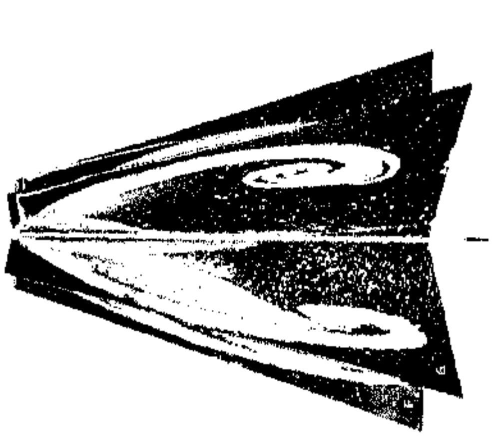

Figure 3. Oil flow visualisation of bubble vortex pattern.

of l, and these points only have been plotted in Fig. 4 for $2\theta=50°$. The improvement in C_p with increasing l, as shown in this figure levels off around $l/L=0.06$ for all three diffusers. The limiting pressure recovery coefficients attained in the present tests were as follows:

2θ	C_p max.
25°	0·73
38°	0·61
50°	0·42

(Note: For fully spread flow with no pressure losses, $C_p=0.995$.)

The exit flow was steady and uniform with the 25° and 38° diffusers. The 50° diffuser exhibited a symmetric double-peaked profile in the exit plane of measurement, with a central core of reversed flow. A tuft survey revealed that in this case the separation bubble did not terminate inside the splitter passages. A free-stagnation point was located on the axis about 4 in downstream of the diffuser exit plane. Tuft exploration indicated that downstream of the free-stagnation point the flow approached uniform conditions quite rapidly. However, the total axial distance to achieve this condition did not appear to be significantly less than for the 38° diffuser.

Tests with six-vane splitters in the 25° and 38° diffusers showed them to be almost equally effective, although the exit flow was somewhat unsteady. Flow visualisation suggested that the bubble inside the passage was less stable in this case. As seen in Fig. 4 the ultimate pressure recovery performance of the six-vane splitters was not superior to the eight-vane splitters.

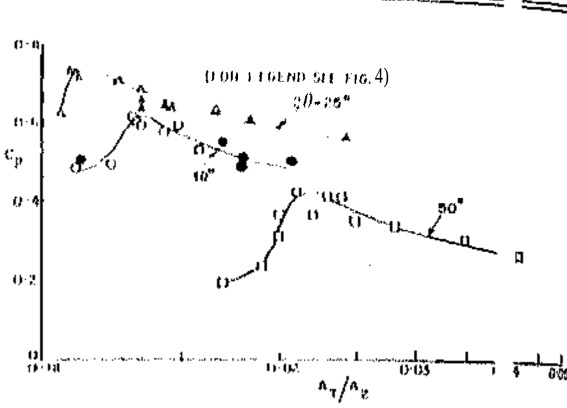

Figure 5. Effect of splitter apex blockage on pressure recovery.

Although a rather wide range of combinations of l/L and d/D produced effective flow spreading with six-vane and eight-vane splitters in the three diffusers, the data indicated that certain combinations were more favourable for best pressure recovery in a given diffuser. The significant parameter appeared to be the trip blockage A_T/A_2 which includes the variations of both l and d. The test data have been re-plotted as C_p versus A_T/A_2 in Fig. 5, which contains the C_p measurements for all trip sizes tested, thus covering a wider range than Fig. 4. It also includes the cases (for the 25° and 38° diffusers) where no trips were used, by taking the estimated blockage area at the splitter junction (due to vane thickness) for A_T. The plot shows more clearly than Fig. 4 that the present data have covered a sufficient range to positively identify the peak value of C_p for each diffuser, and provides a good indication of the fundamental role of the apex blockage.

To understand the manner in which, A_T/A_2 influenced the pressure recovery characteristics, the variation of the bubble size and the exit profile were observed with gradually increasing trip blockage. The centre of the eddy in the bubble (see Fig. 3) was found to move progressively downstream and away from the axis, accompanied by a downstream movement of the re-attachment location in the inner corner of the passages. Correspondingly, the exit profile which initially had a small bulge near the axis gradually straightened out, became nearly uniform at a critical value of trip blockage and then developed a

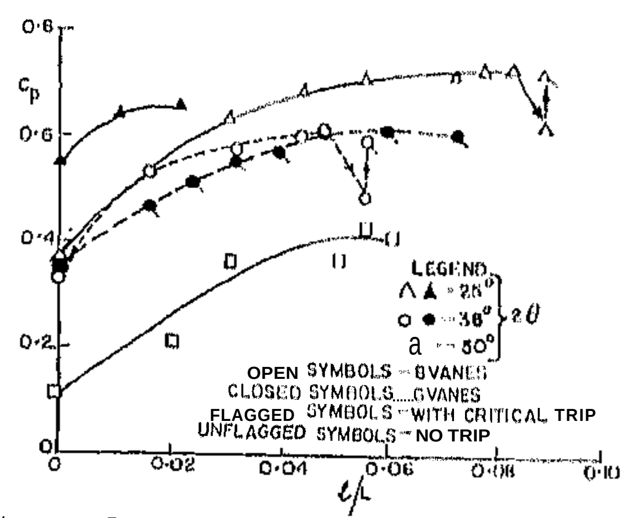

Figure 4. Pressure recovery improvement with splitter cut-off.

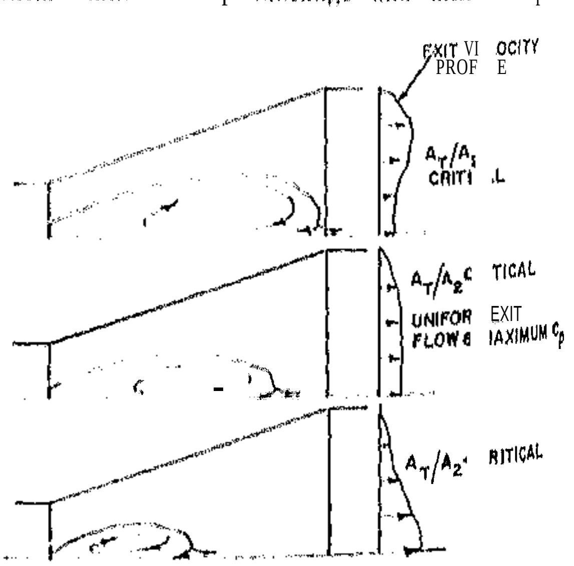

Figure 6. Effect of splitter apex blockage on exit profile.

double-peaked shape (Fig. 6). A maximum in C_p was attained simultaneously with uniform exit flow.

The effect of inlet velocity profile was checked by placing a wire-gauze ring at a position 3 in (0·08 m) up-stream of the diffuser inlet plane. With a symmetrical velocity profile, the effectiveness of the splitters was retained. When the gauze ring was placed eccentrically, however, the resulting asymmetric inlet velocity profile caused the corner-bubble flow to collapse in some of the splitter passages, leading to fluctuating exit flow. The radial vane splitter configuration is evidently sensitive to inlet asymmetry; it is, however, thought that some degree of tolerance in such a case may be achieved by locating the trip eccentrically to ensure corner-bubble flow in all splitter passages.

Supporting experiments with a triangular duct model, representing one of the passages of an eight-vane splitter in a 38° diffuser, to the same scale confirmed the qualitative aspects of the trip-induced corner-bubble flow. The change-over from the centre-jet to corner-bubble flow with increasing trip projection occurred suddenly at a particular value of trip blockage. Further increase of trip blockage was accompanied by changes in the exit profile similar to that observed with the conical diffuser. A small but distinct hysterisis was noted in the collapse of the corner-bubble with decreasing trip ,si/.e, which occurred as suddenly but at a somewhat smaller value of the trip blockage than that which had produced the corner-bubble flow, At: a trip setting close to this critical size, the flow alternated randomly between the centre-jet and corner-bubble patterns; such a switching could also be induced by a mechanical disturbance.

These characteristics are suggestive of a Coanda-type mechanism responsible for the flow attachment to the diffuser wall. If such a mechanism is operative in (he present instance, this would place a limit on the wall angle (i.e. diffuser semi-cone angle) for flow attachment and the existence of the bubble-vortex flow. According to the present results, however, such a limit would appear to lie well beyond the minimum diffuser length for flow spreading through area-ratio 15. The practical advantage, if any, of a closer approach to the limiting expansion angle for smaller area-ratio diffusers remains to be investigated.

6. Concluding Remarks

The present experiments have fully confirmed the effectiveness of radial splitters in large area ratio conical diffusers of total expansion angles up to 50°. For area-ratio=15, the optimum diffuser angle to achieve uniform exit flow in the shortest axial distance appears to be close to 40°, and with this arrangement a maximum pressure recovery coefficient of about 0·6 is possible. A higher C_p value (exceeding 0·7) for the same area-ratio can be attained with a reduced expansion angle of 25°.

Since the pressure recovery of the diffuser with splitters is essentially that of the individual passages, a comparison with conical diffuser performance is of interest. The effective expansion angle of the splitter passages in the 38° diffuser is 14°. Data on conical diffusers of area-ratio as large as 15 is scarce for the obvious reason of large-scale flow unsteadiness at exit. A 15° diffuser with area-ratio 7·55 was found to yield a pressure recovery coefficient between 0·55 and 0·57 (Ref. 2). It is evident that with the corner-bubble flow, the pressure recovery characteristics of triangular expanding ducts are superior and provide much better exit flow conditions than would be expected with an equivalent conical diffuser, particularly at the large area-ratio values considered here.

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